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HARDENED TUNED-WALL PLASTIC RADOMES FOR MILITARY RADARS

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FABRICATION OF XP PLASTIC RADOME PANELS

A. BACKGROUND

XP (stretched polypropylene) film is perhaps the most effective material for construction of hardened dielectric walls. It has excellent fragment-defeat properties, a low relative dielectric constant (2.3) and a very low loss tangent (0.005). For low-loss materials, reflection losses are determined by the dielectric constant and absorption losses by the loss tangent. A perfect radome material would have a dielectric constant of one and a loss tangent of zero. Additionally, XP is self bonding under heat and pressure, allowing construction of homogeneous, tuned-wall design. The wall thickness is chosen to be an integral number of half wavelengths in the material to take advantage of cancelling out reflections at the inner wall; loss in beam intensity is then mainly due to absorption in the wall. (1) The resulting thick-wall radome allows efficient r-f transmission and provides a high level of ballistic protection against fragmentation munitions.

The AN/TPQ-37 is the first radar antenna considered for hardening against fragment munitions attack. It is designed to accurately locate artillery and rocket launch weapons by detection, tracking, and back-plotting trajectories of in-flight warheads, thus placing strict requirements on radome transparency to r-f transmission. Since this effort was directed toward producing high quality radomes for the AN/TPQ-37 antenna, the processing techniques developed are applicable toward the construction of high efficiency tuned-wall radomes for a wide variety of military radars.

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The basic processing parameters and methods for producing XP film laminate panels with close dimensional tolerances were first established with laboratory-scale experiments. Film pad layup, assembly, and handling techniques were developed along with dependence of laminate thickness and quality on lamination, temperature, pressure, and time. Laboratory experiments were followed with scaled-up pilot plant runs. Figure 1 is a flow diagram that summarizes the processing steps for construction of XP film radome components; it traces the polypropylene polymer from pellet form to the radome sub-modular panel.

The XP film used in this work was prepared at Phillips Scientific Corporation by hot stretching flat, tubular polypropylene film at 320 F to approximately 12 times its original length and an average thickness of 0.0014 inch. Polypropylene is a highly crystalline polymer (65% crystallinity) and film stretching results in highly oriented molecular chains that increase the polymer tensile strength from 4300 to 50,000 psi in the stretch direction. (2) However, the film has low strength (40 psi) in the transverse direction. Because of the unidirectional strength of the stretched film, successive layers must be cross-plied at 90 degrees to produce pads of optimal ballistic

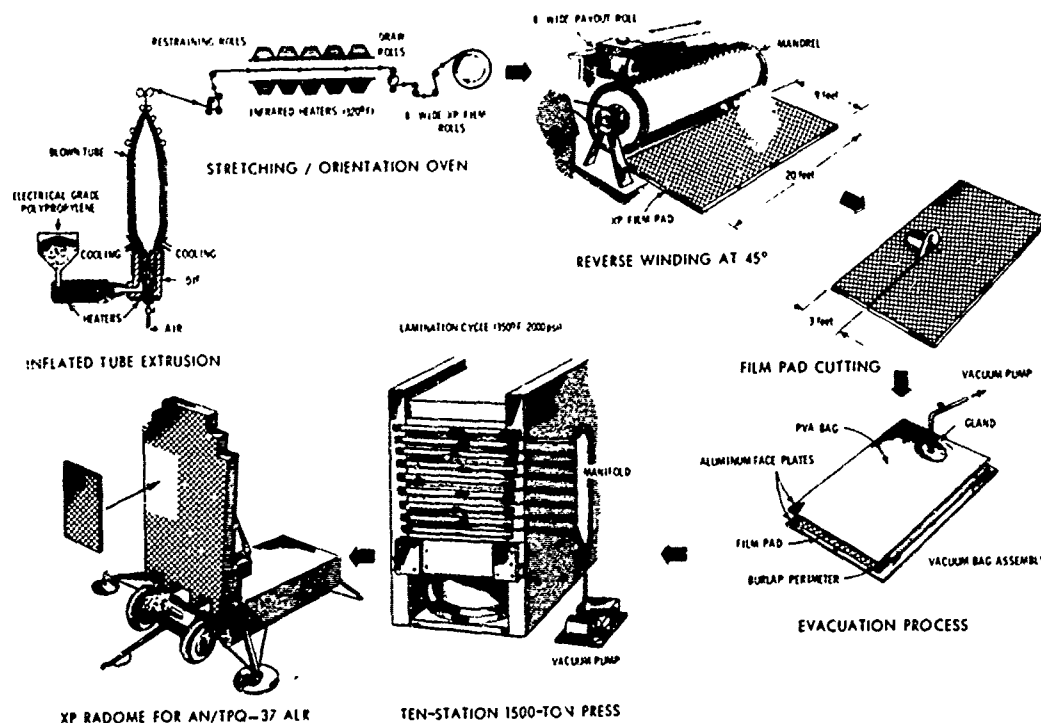


Figure 1. Flow sheet for XP radome panels.

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effectiveness. This layup process is efficiently accomplished by reverse filament winding; an 8-inch-wide strip of film is mandrel wound at opposite 45-degree angles to the mandrel axis to produce a film pad consisting of interleaved film plies. Film layup for this work was accomplished on a 3-foot-diameter, 21-foot-long mandrel. Resistance wires placed along the length and at the ends of the mandrel before winding were electrically heated after winding to cut a 9x20-foot pad from the mandrel. The large pads were subsequently cut into 18x36-inch subpads and subdivided into 1, 2, 4, and 8-oz/sq ft areal density sections for assembly of lightweight armor components. Planned efforts for construction of radome panels will utilize XP pads of greater thickness to improve laminate assembly efficiency.

As conventionally molded, XP laminates entrap air at the interstices of the interleaved construction. Consequently, successive plies of film are not well bonded to each other. This contributes largely to poor structural properties, including panel delamination under shear, flexure, temperature variation, and low velocity (non-ballistic) impact. For application as radome components, XP panels must be constructed free of entrapped air and moisture with uniform interply bonding. Theoretical mass density (exclusion of air) is also desirable to minimize attenuation and reflection of radar signals. Furthermore, to maintain the high ballistic properties of the stretched film, the panel fabrication process must not disturb polymer orientation. These requirements are then basic to the XP film lamination schedule.

B. Model Experiments

The objective of the laboratory-scale experiments was to develop the procedures for producing thick XP laminate with close tolerances (1.045 ± 0.015 inches thick) that would satisfy the requirements of a hardened flat radome tuned-wall structure for the AN/TPQ-37 antenna. A series of experiments was conducted on 6x6-inch test specimens to determine the effects of lamination pressure, temperature, and time on the laminate final thickness and density. A Lawto-matic hydraulic press rated at 50 tons capacity was used in this phase of the study. The press capacity of 50 tons and a specimen size of 6x6 inches allowed variation in lamination pressure up to 2800 psi. The XP film specimens were heated and cooled by conductive heat transport from the press platens; the platens contain electrical heating elements of 7200 watts capacity as well as cores for flow of cooling water. The platen temperature could be varied from room temperature to 600 F and controlled to within ± 1 F. Both rapid and slow cooling were achieved by adjusting the cooling water flow rate with a throttling valve.

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Initial experiments simply involved hand stacking approximately ten individual film modules, each measuring 6x6x0.1 inch, to form a 6x6x1-inch pad. The film pad was then placed between 1/8-inch-thick aluminum plates and laminated by the Lawtomatic press, using only pressure to remove the air between the film plies. (Note that a 1-inch-thick section contains approximately 800 layers of film!) Although this procedure produced rigid laminates, air entrapment was observed. This took the form of a striated, opaque, white haze within the laminate resulting from light reflections and scattering at the air-film boundaries. (Air-free laminates are characterized by translucency and a light amber hue.) A number of experiments were performed without success to eliminate air entrapment, including preheating the film panel to 215 F and slow application of platen pressure. It immediately became apparent that simple means would not lead to the degree of air removal required to produce laminates of theoretical density.

The philosophy of the experimental program was to proceed from simple to more sophisticated techniques to arrive at a cost-optimal lamination procedure applicable to end-item component fabrication.

Lamination of theoretical density XP panels ultimately required careful material preparation followed by vacuum treatment. Approximately 0.2-inch-thick film pads were cleanly cut to the 6x6-inch specimen size with a book-bindery type power shearing machine. The quick one-step shearing action of this machine induced no appreciable temperature rise within the cutting blade or XP material. Consequently, a clean, unfused cut was achieved. The conventional rotary cutting wheel employed for cutting fabrics and plastic film caused localized fusing at the XP film edges after a relatively short time (approximately 10 seconds) due to heat buildup within the wheel. Fusing of the pad edge hinders removal of entrapped air.

After cutting, film pads were hand stacked to the desired thickness and placed between flat 1/8-inch aluminum caul plates. Gloves were worn when handling the film and assembly was conducted in a semiclean room. Oil and water vapor contamination will result in weak bonding; foreign matter inclusions, particularly metallic, will degrade r-f transmission characteristics. Four layers of commercial-grade coarse-weave burlap cloth were placed in contact with the XP pad along the perimeter to provide a path for air removal. The entire XP/aluminum/burlap assembly was enveloped in a 4-mil-thick polyvinyl alcohol (PVA) plastic film bag; the bag was heat sealed with a 1000-watt Vertrod thermal pulse heat-sealing machine to form an airtight envelope. A vacuum was applied to the assembly employing a mechanical

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Cenco vacuum pump to evacuate air from the XP film pad. Air flow was through a rubber-gasketed gland attached to one end of the PVA bag. An evacuation time of approximately one-half hour was required to achieve near total air removal; this was indicated by a reading of 29.1 inches of mercury on a vacuum gage. Since the PVA bag was deflated over the assembly, atmospheric pressure (14.7 psi) was effectively applied to the burlap/XP perimeter; this minimized slippage of the XP film pad during pressure and heat application. Laminate assemblies were then introduced to preheated press platens; the assembly was held under vacuum for the entire cycle.

The lamination process variables investigated included temperatures from 330 F to 350 F, pressures from 1000 psi to 2700 psi, and time cycles to 1-1/2 hours for heating and 2 hours for cooling. Copper constantan thermocouples connected to a Biddle potentiometer were placed on the top surface and at midthickness of the XP panel to accurately measure temperature histories. Since heat was supplied unidirectionally by conduction from the platens through the aluminum plates to the XP panel, the temperature-time profile across the panel thickness could be calculated by the following rapidly converging series:

$$(T-T_0)/(T_1-T_0) = 2/\pi \sum_{n=1}^{\infty} (1-(-1)^n/n) \exp(-\alpha n^2 \pi^2 t/X^2) \sin(n\pi x/X).$$

Here T = temperature at time t and location x ,
 T_0 = platen temperature,
 T_1 = room temperature,
 α = XP thermal diffusivity,
and X = panel thickness.

The time required for the entire XP panel to reach a final temperature T_0 was calculated by the formula:

$$\text{Time} = \frac{\text{Heat Content}}{\text{Heat Transfer Rate}} = \frac{mC_p (T_0-T_1)}{(kA(T_0-T_a)/(X/2))}$$

where m = panel mass,
 C_p = XP specific heat,
 k = XP thermal conductivity,
 A = panel area,
and $T_a = (T_0+T_1)/2$ = average temperature.

Close agreement was obtained between measured and calculated temperatures and lamination times.

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The laboratory-scale experiments clearly illustrated that both temperature and pressure have a significant effect on laminated XP film constructions. Rigid, air-free laminate specimens with little loss in polymer orientation or ballistic performance were obtained at 350 F and 2000 psi. Laminates constructed at lower temperatures (330 F to 345 F) possessed poor interply bonding. At high temperatures (355 F), excessive flow of XP occurred; this was indicated by material flash at the laminate edges. Molding XP film requires sufficient pressure to prevent film shrinkage, loss of dimensional configuration, and relaxation of the oriented polymer. The XP film is in a highly oriented condition. Exposure to temperatures near the stretching temperature can induce transition to simple polypropylene. For pressures below 1000 psi, loss in polymer orientation was evidenced by sample shrinkage and appreciable loss in ballistic performance. At pressures of 2000 psi and above, specimen dimensions other than thickness were maintained with no deterioration in ballistic performance.

Laminating at a given platen temperature was conducted for 70 minutes; this was generally sufficient to maintain the specimen midthickness at the platen temperature for a hold time of 5 minutes. Specimens were cooled under pressure to an internal temperature of 70 F. No change in laminate quality could be observed between rapid and slow cooling rates as long as pressure was maintained during cooling. In general, a 60-minute cooling cycle was employed.

Since the primary objective was to construct XP panels with close thickness tolerances, particular attention was devoted to determining the functional relationship between laminate final and initial thicknesses as well as the effects of laminating temperature, pressure, and time on this relation. Figure 2 shows the effect of initial thickness on final thickness for a series of constant temperature/pressure combinations. Figure 2a is constructed at a fixed lamination temperature of 350 F; Figure 2b is at a constant lamination pressure of 2000 psi. The lamination time is constant at 70 minutes. Lamination times greater than 70 minutes produced only small additional reductions in thickness and some disorientation of the XP polymer. An average thickness reduction of 14% was experienced for 6x6-inch specimens under the laminating conditions of 350 F and 2000 psi. Consequently, it would appear that 1.210 inches of XP film is required to achieve the desired final laminate thickness of 1.045 inches. This was verified and replicated through additional laboratory experiments. Also, a thickness tolerance of ± 0.015 inch was obtained for all 6x6-inch specimens of nominal 1-inch thickness. It should be noted that minor flash was detected at the upper and lower face perimeters of the 6x6-inch specimens, indicating melting on the surfaces in contact with the platens.

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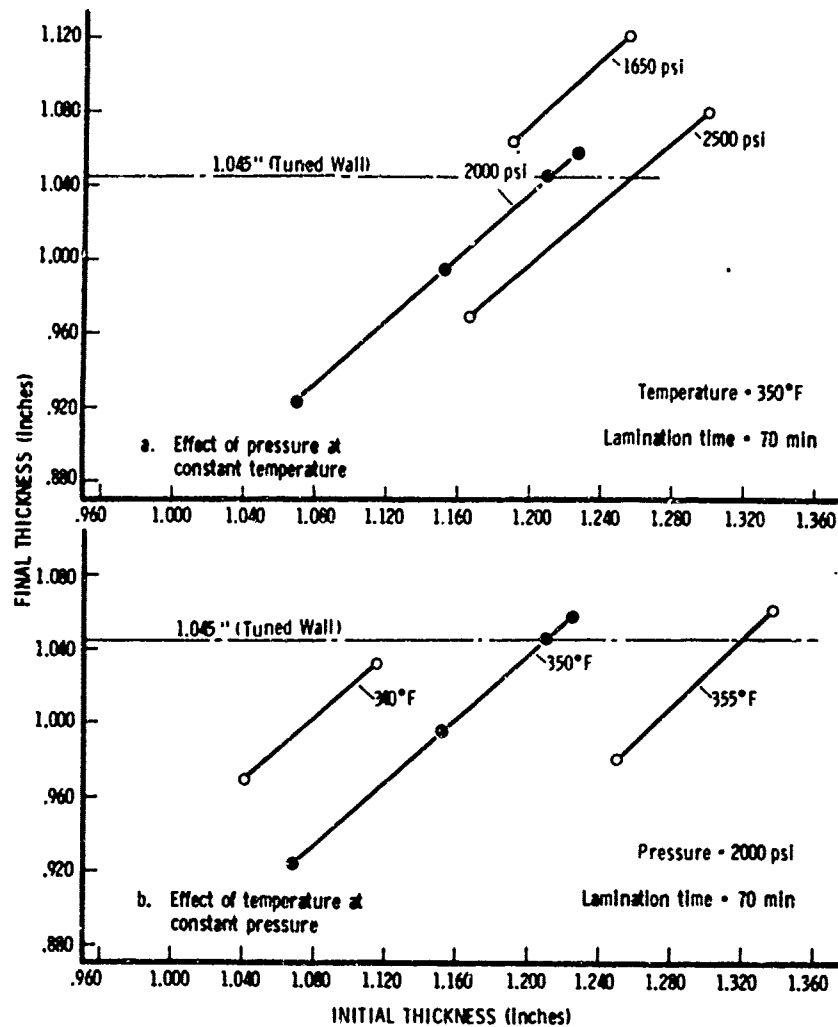


Figure 2. XP laminate thickness variation, 6x6 test specimens.

Lamination parameters and fabrication techniques were defined in the laboratory scale phase. This effort formed the basis for pilot plant scale-up of the XP laminate fabrication process to construction of full-scale components for radome walls.

C. Pilot-Scale Practice

The fabrication of radome wall panels under the conditions developed in the laboratory required a large-area, high-tonnage press with heating and cooling capabilities. Industrial press construction

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included a 32-inch-diameter hydraulic piston with a 1500-ton capacity and 11 platens (measuring 50x36 inches); this allows ten-station lamination. The platens were heated by saturated steam and cooled by line water recirculating through a cooling tower.

Because of the high lamination pressure required, it was necessary that the XP film pad cover most of the 50x36-inch platen area; this insured production of flat laminates with uniform thickness and, at the same time, prevented possible scoring of the press platens. Accordingly, 46x32-inch sections were cut from 48x36-inch film pads and handstacked similar to the laboratory specimens. The 46x32-inch size represented the largest rectangular pad, consistent with press requirements, that could be cut from the available 48x36-inch film stock. This size represented a 40 to 1 scale-up in laminate area (1472 versus 36 square inches) from the laboratory experiments. All film layup and assembly work was done in a semiclean room to minimize inclusions in the film pad. Film pads 1.210-inch thick were sandwiched between flat 1/8-inch plates (48x36 inches) of aluminum, surrounded with burlap at the panel perimeter and sealed in a PVA film bag. The assembly was evacuated to a vacuum gage reading of 29 inches of mercury for at least 6 hours before laminating to remove all traces of air and water vapor. Thermocouples (copper-constantan) were placed at the outer surfaces and midthickness of the XP pads to monitor temperatures. The evacuated assemblies were placed in the laminating press with several sheets of heavy paper cushioning pads inserted between the assembly and press platens.

The lamination cycle for the nominal 1.2-inch-thick pads included: (1) placement of assembly between the press platens; (2) steam heating from room temperature to 350 F (70 minutes); (3) maintaining temperature at midthickness for 10 minutes; (4) air cooling to 320 F for 30 minutes to insure against thermal shock of press and laminate; (5) water cooling to 70 F (80 minutes) and, finally, (6) removing the laminated XP panel from the press.

Laminated XP film panels are not resistant to surface abrasion; exposed surfaces peel or flake under abrasive forces. A thin shield of pure polypropylene applied to each face is a sufficient protective cover for the ballistic, dielectric panel; polypropylene covers are considered r-f compatible with the core XP panel. Four plies of 2.5-mil polypropylene film were laminated to both upper and lower surfaces of select panels; a high-tonnage press was required for this step. The covering cycle included heating to 340 F from room temperature (30 minutes), air cooling (10 minutes), and water cooling (30 minutes), all at 2000 psi pressure. A vacuum was held on the XP laminate/polypropylene sandwich for the covering cycle as in

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the lamination process. The 340 F temperature was determined by laboratory experiments with the 6x6-inch test specimens. At 330 F, poor bonding of the polypropylene covers resulted; at 350 F, excessive cover material flow occurred along with panel slippage.

The specific gravity of XP film has been determined as 0.91; this implies a theoretical areal density of 4.73 psf for a 1-inch-thick laminate. The areal densities for the 46x32-inch XP film laminate panels prepared in this work ranged from 4.73 to 4.74 psf per inch of thickness. Based on measurement accuracies for determination of these areal densities (± 0.001 inch for the thickness dimension and ± 0.031 inch for the length and width dimensions), the laminate panels prepared here can be considered to be at theoretical density. Figure 3 illustrates the relative size of laboratory and full-scale laminates.

A number of XP film laminate cutting techniques were investigated in preparing the environmental test panels. These included abrasive cutoff wheels, scalloped and multitooth band and saber saws, high-temperature/high-velocity air jets, and a 10-kilowatt CO₂ continuous wave laser beam available at AVCO Corporation, Everett, MA. Cutting was best achieved with an 8-tpi blade on a band saw operating at medium speed with the blade mounted in the reverse direction. This technique generated a heat-induced cut with minimal delamination and material flow. The conventional rip cut induced excessive panel delamination while melt-type cuts induced excessive material flow. The minor delamination experienced at the cut edges by the "backward saw" technique was sealed by fusion with a hot plate. This insured against possible nucleating sites for delamination and deterioration in the environmental testing phase. The cutting experiments confirmed a prior hypothesis that XP film laminates for radome wall construction should be molded to size eliminating unnecessary cutting or machining after lamination.

BALLISTIC DESCRIPTION OF XP RADOMES

A. Experimental Procedure

Terminal ballistic experiments to define the performance level of XP plastic armor for fragment-resistant radomes were carried out with munition fragment projectiles ranging from 2 to 80 grains in mass. Ballistic tests were also conducted with Army fragment-simulating projectiles (FSP) in accordance with Reference 3.

The fragments used in the ballistic experiments were recovered from the static detonation of foreign munition warheads. These included an 82-mm mortar HE shell of gray cast iron and a 100-mm HE

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projectile of plain carbon steel. The metallurgy, constitutive properties, and geometry of the fragment populations obtained from these munitions are discussed in Reference 4. Soviet conventional munitions are generally of gray cast iron or plain carbon steel. The ballistic model developed in this work does not distinguish between fragments of differing compositions, since the two behave similarly in their ballistic impact on XP armor.



Figure 3. Laboratory and mockup radome panels of XP laminate.

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Measurements for each fragment test round included mass, strike velocity, and residual velocity, and the area contained in the shot-line projection of the fragment on the target plane at impact. A schematic diagram of the ballistic test arrangement is shown in Figure 4.

Each fragment was launched from a caliber .540 smooth bore barrel. Fragment velocities were determined by measurement of flight time over a fixed distance; this was accomplished by time counting with 10 MHz frequency counters between successive breaks in silver-line circuit paper grids. Fragment velocity at the target was obtained from instrument velocity by correcting the latter velocity for air resistance; these calculations are described in Reference 5.

The area contained in the shot-line projection of the fragment on the target plane at impact was recorded on a paper yaw card placed parallel to and directly before the target. Area measurements were made on a 10X magnification of the preimpact profile recorded on the yaw card.

The XP film test panels consisted of stacked plies of Phillips Scientific Corporation XP plastic film (polypropylene film stretched 12 to 1) in both unbonded and laminated form. The unbonded panels were simply multiple plies of XP cut into 16x20-inch sections

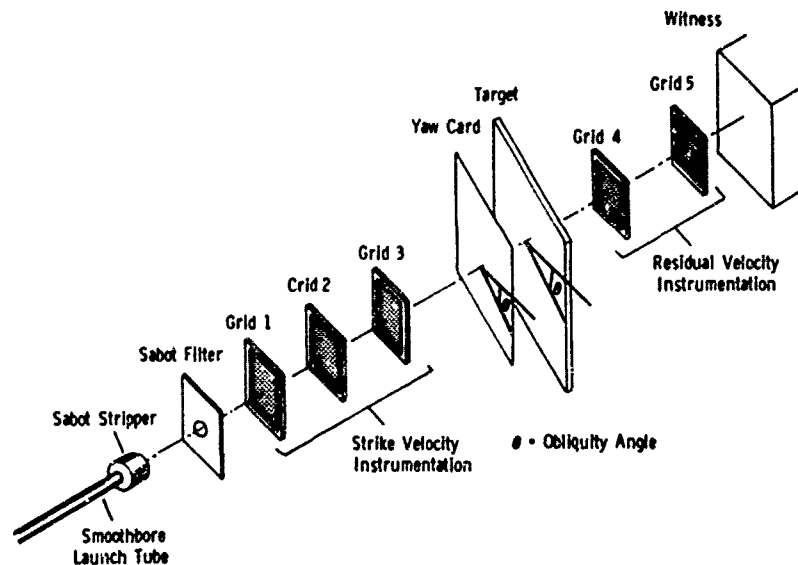


Figure 4. Schematic diagram of ballistic test arrangement.

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and held together with continuous nylon stitching along a grid with a 3x3-inch mesh. The laminated panels were formed by bonding plies of film at 320 to 330 F and 1000 psi. In the case of the laminated XP targets, individual test rounds were fired at squares of 4x4 inches cut from parent panels. No ballistic distinction was made between unbonded and laminated XP film in this study.

B. Terminal Ballistic Model

The fragment terminal ballistic data for XP and other light-weight armors is included in Reference 6. Fragment strike and residual velocities are tabulated for each test round along with the fragment identification number, fragment mass m , and the area contained in the shot-line projection of the fragment on the target plane at impact (impact area A_I). The calculated shape factor based on this area, $K=m/A_I^{3/2}$, is also included.

The general technique for determination of a residual velocity model is to assume some form for the residual velocity function and then fit the function to experimental residual velocity data usually by a least-squares technique. The ballistic limit function is then the strike velocity for which the residual velocity vanishes. In this work we used the fragment residual velocity data to first establish munition fragment ballistic limit data, then represented the ballistic limit (V_L , ft/sec) as a function of fragment mass (m , grains), impact area (A , in.²), and target areal density (σ , grains/in.²) (7,8):

$$V_L = a A_I^b m^c \sigma^k = a (A \sec \theta)^b m^c \sigma^k.$$

The constants a , b , c , and k were determined to be 711, 0.192, -0.415, and 0.653 by multiple linear regression of $\log V_L$ on $\log (A \sec \theta)$, $\log m$, and $\log \sigma$.

Given this model, fragment residual velocity V_R can then be estimated with the simple energy balance model: (6,9)

$$V_R^2 = (m (<m+\sigma A_I)) (V_S^2 - V_L^2) \quad V_S \geq V_L$$

where V_S is strike velocity.

STABILITY OF XP PLASTIC RADOMES

A number of tests were selected to investigate the stability of molded XP armor with temperature and aging in several environments. The tests included exposure to extreme conditions of the intermediate

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and wet climatic categories for Army combat materiel. These are categories 1, 2, 5, and 6 defined in Table 2-1 of Army Regulation, AR 70-38.(10) Since an XP laminate radome would be continuously exposed to the environment, the primary interest in these tests was in ballistic and dimensional stability.

Test specimens were cut from the nominal 1-inch-thick XP panels. Measurements included:

a. The V_{50} ballistic limit velocity with the 17-grain (.22 caliber) Army fragment-simulating projectile:

- (1) at room temperature (baseline)
- (2) at -30 F
- (3) at 160 F
- (4) after temperature/humidity cycling by Method 507 of MIL-STD-810B(11)
- (5) after accelerated outdoor exposure (modification of ASTM D1435-69).(12)

b. Dimensional and weight changes after temperature/humidity cycling, Procedure I of Method 507 of Reference 1, and accelerated outdoor weathering.

c. Dimensional and weight changes after water immersion at room temperature for up to five weeks and after a 2-hour water boil.(13)

d. Appearance changes after all tests.

The results of the tests are presented and discussed in detail within Reference 6. Briefly, the effect of temperature on V_{50} ballistic limit velocity for nominal 1-inch-thick panels is given by Figure 5. The V_{50} velocity increases to 112% of its room temperature value at -30 F and retains 92% at 160 F. Laminates exposed to humidity/temperature cycling retained 98% of the ballistic limit velocity of the control targets.

No change in weight could be detected after humidity/temperature cycling and after water immersion. Small dimensional changes did occur; both lengths and widths decreased 1/16 inch in distances of 10 and 8 inches, and the average gain in thickness was 0.009 inch. However, a heat preconditioning step at 200 F has been found to dimensionally stabilize XP laminates.

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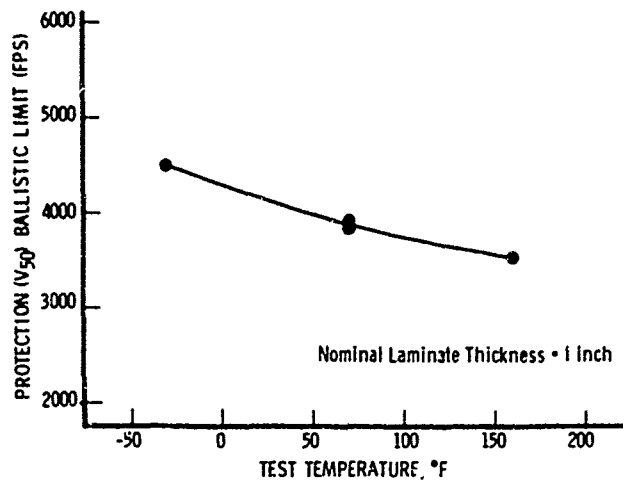


Figure 5. XP laminate ballistic limit variation with temperature.

CONCLUSIONS

1. Research and development have been accomplished which makes feasible the utilization of XP plastic film, an all-organic (polypropylene) material that combines effective fragment-penetration resistance with low r-f loss characteristics, for hardening radar antennae. The technology base includes:

a. Precise determination of the lamination process variables of temperature, pressure, and time, as well as the functional relationship between final laminate thickness and initial film thickness to produce controlled fusion laminates without orientation release of the plastic film.

b. Development of film layup, assembly, and evacuation techniques for total removal of entrapped air and water vapor in multiple-ply XP film assemblies before and during lamination.

2. Laboratory and pilot plant experiments have been conducted to demonstrate fabrication of XP plastic film molded panels with:

a. Thickness of close dimensional tolerance for tuned-wall radome wall designs that offer high r-f transparency and vulnerability reduction to fragmenting munition threats.

b. Sizes that permit efficient modular preconstruction of dielectric walls.

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